US Army Corps of Engineers
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Technical Report REMR-CS-55
February 1998

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Evaluation of Criteria for Uniformity of Roller-Compacted Concrete

by Brian H. Green, Billy D. Neeley, Toy S. Poole

Prepared for Headquarters, U.S. Army Corps of Engineers

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	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
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HY	Hydraulics	OM	Operations Management
CO	Coastal		

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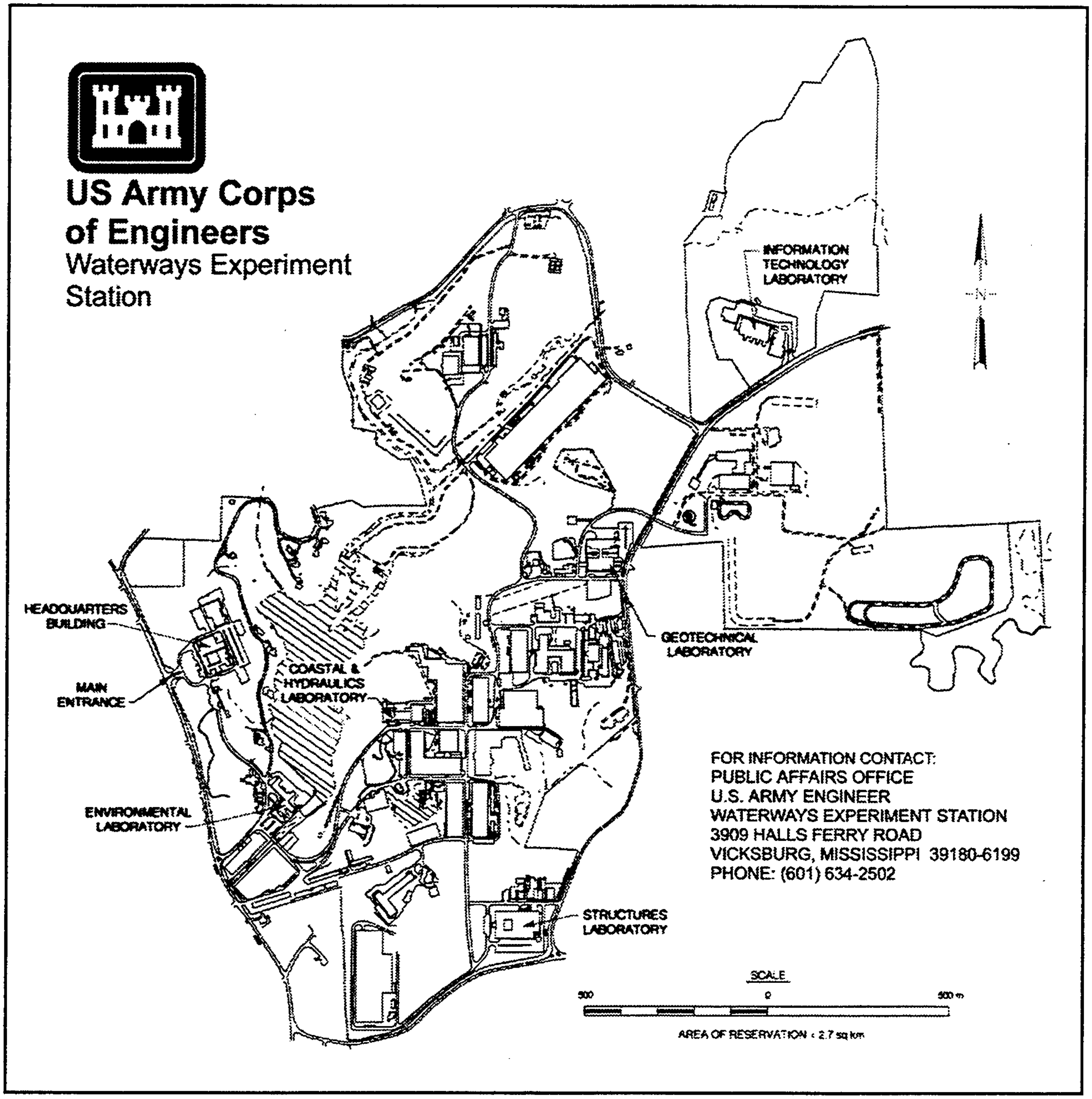

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Contents

Preface

This report was prepared by the Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), under the sponsorship of Headquarters, U.S. Army Corps of Engineers (HQUSACE), as a part of Civil Works Research Work Unit 32639, "Repair and Rehabilitation of Dams," for which Mr. James E. McDonald, SL, is the Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Mr. M. K. Lee (CECW-EG), HQUSACE, is the REMR Technical Monitor. Dr. Tony C. Liu (CERD-C), HQUSACE, is the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Harold C. Tohlen (CECW-O) and Dr. Liu serve as the REMR Overview Committee.

The study was conducted under the general supervision of Dr. Bryant Mather, Director, SL, and Mr. John Q. Ehrgott, Assistant Director, SL. Direct supervision was provided by Dr. Paul F. Mlakar, Chief, Concrete and Materials Division (CMD), Mr. Edward F. O'Neil, Acting Chief, Engineering Mechanics Branch (EMB), and Dr. Newell Brabston, Chief, Engineering Sciences Branch (ESB). Messrs. Brian H. Green and Billy D. Neeley, EMB, and Dr. Toy S. Poole, ESB, prepared this report. The authors acknowledge the assistance of Mr. Steven A. Ragan, former Chief, EMB, and Messrs. Michael K. Lloyd, Jimmy W. Hall III, Dan Wilson, Roy C. Gill, Olen K. Loyd, and Michael Hedrick, EMB, in preparing and evaluating the concrete mixtures in this investigation.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

1 Introduction

Background

Roller-compacted concrete (RCC) is used by the Corps of Engineers to provide an approach to economical dam construction. A relatively low-cost concrete mixture, with minimum water and cement content, is mixed and then placed economically by using large earthmoving equipment. The concrete is then consolidated by vibrating steel-wheel rollers, resulting in much higher strengths than could be obtained with a similar mixture without this type of consolidation.

The Corps of Engineers gives guidance on the production of RCC in EM 1110-2-2006 (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1992b). A major advantage that RCC dams have over other types of dams is rapid construction. Maximum placement rates of 4,400 to 9,500 m^3 (5,800 to 12,400 yd^3) per day have been achieved. A key part of this placement rate is the mixer used to produce the RCC. RCC has been mixed both in tilting-drum mixers and pugmill mixers. Experience indicates that a pugmill mixer produces faster and more effective mixing due to its intense shearing action. Regardless of the type of mixer, the ability to produce a uniformly mixed RCC mixture in a minimal amount of time is paramount.

Current Uniformity Requirements

Mixer uniformity requirements (Table 1), currently found in Corps of Engineers Civil Works Guide Specification (CWGS)-03360, "Roller-Compacted Concrete for Mass Concrete Construction," (HQUSACE 1994) are the same requirements as those given in CWGS-03305 "Mass Concrete," (HQUSACE 1992a) for nonroller-compacted mass concrete with three exceptions: (a) The requirement for water content is included in the abbreviated testing, (b) the Vebe consistency procedure is included in the regular testing, and (c) there are no requirements for unit weight of air-free mortar, air content, and slump. The coarse-aggregate content, compressive-strength, and water-content procedures are applicable to both mass concrete and RCC. The Vebe consistency procedure is normally used only for RCC. The slump, air content, and unit weight of air-free mortar procedures are normally used only for mass concrete. However, for air-entrained RCC, the air content and unit weight of air-free mortar procedures could also apply. There has not been a determination of the

Table 1
Current Ranges of Parameters for Mixer Uniformity for RCC (CWGS-03360) (HQUSACE 1994)

Parameter	Regular Tests Allowable Maximum Range for Average of Three Batches	Abbreviated Tests Allowable Maximum Range for One Batch
Unit weight of air-free mortar, kg/m³ (lb/ft³)	32.0 (2.0)[1]	32.0 (2.0)[1]
Air content, percent	1.0[1]	--
Coarse aggregate, percent	6.0	6.0
Compressive strength at 7 days age, range as percent of the mean	10.0	10.0
Water content, percent	1.5	1.5
Consistency, modified Vebe, sec	7.0	--

[1] Not part of requirements of CWGS-03360; values taken from CWGS-03305 and suggested for use with air-entrained RCC.

suitability of these uniformity requirements for use with RCC. A laboratory study was needed to validate each of these requirements.

Mixer uniformity is evaluated using CRD-C 55, "Test Method for Within-Batch Uniformity of Freshly Mixed Concrete," (U.S. Army Engineer Waterways Experiment Station (USAEWES) 1949b). This procedure directs that samples of concrete be taken from the first, middle, and last portions of a batch of concrete as it is discharged from the mixer being evaluated. Each sample is evaluated for the properties listed in Table 1. Acceptance requirements are then based on the range of test results among the three samples.

Objective

The objective of this investigation was to evaluate the current mixer uniformity requirements for RCC in a controlled laboratory study. The results would then be used to validate current requirements or to recommend changes.

Approach

Ten similar batches of an air-entrained RCC mixture and ten similar batches of a nonair-entrained RCC mixture were mixed and evaluated according to CRD-C 55 (USAEWES 1949b). Many of the measurements were made in non-SI units and converted to SI units using conversion values in American Society for Testing and Materials (ASTM) E 380 (ASTM 1994m). Each batch was mixed for a period of time believed to be more than adequate to achieve

uniform mixing. From this evaluation, a determination was made of the maximum ranges among test results (from the three samples from a batch) that could be expected to occur on well mixed concrete due to random sampling and testing variation. Higher values could then be taken as an indication of inadequate uniformity.

2 Research Program

Materials

The materials used in the two RCC mixtures are listed below. The numbers in parentheses are Concrete Material Division (CMD), identification numbers assigned to ensure traceability.

Cement

Portland cement, Type II (930338)

The portland cement conformed to requirements for Type II of ASTM C 150 (ASTM 1994f). Analyses results on the cement are given in Table 2.

Pozzolan

Fly ash, Class F (930340)

The fly ash conformed to requirements for Class F of ASTM C 618 (ASTM 1994k). Analyses results on the fly ash are given in Table 3.

Aggregates

Natural sand fine aggregate (940236)

19.0-mm (3/4-in.) nominal maximum size (NMS) crushed limestone coarse aggregate (940297)

37.5-mm (1-1/2-in.) NMS crushed limestone coarse aggregate (930356)

Limestone crusher dust (940304)

The sieve analysis (ASTM C 136 (ASTM 1994e)) of each aggregate and values of absorption and specific gravity (ASTM C 127 (coarse aggregate) and C 128 (fine aggregate)) (ASTM 1994c,d) are given in Table 4.

Table 2
Cement Chemical and Physical Analyses (Note references ASTM 1994f)

Company: Lone Star Industries
Location: Cape Girardeau, MO
Contract No.: ASTM C 150 (ASTM 1994f), II, LA, HH
Contract No.:
Project: Roller-Compacted Concrete

Test Report No.: WES -158-93
Program: Single Sample
CTD No.: 930338
Job No.: ACSAY08001S0001
Date Sampled: 7 Sep 93

9/20/93 Tests complete, material

Chemical Analysis	Results	Retest	ASTM C 618 Spec Limits Type II
SiO_2, %	21.1		20.0 min
Al_2O_3, %	3.8		6.0 max
Fe_2O_3, %	2.9		6.0 max
CaO, %	62.9		--
MgO, %	3.7		6.0 max
SO_3, %	3.0		3.0 max
Loss of ignition, %	1.2		3.0 max
Insoluble residue, %	0.15		0.75 max
Na_2O, %	0.09		--
K_2O, %	0.54		--
Available-total as Na_2O, %	0.44		0.60 max
TiO_2, %	0.20		--
P_2O_5, %	0.10		--
C_3A, %	6		8 max
C_3S, %	54		--
C_2S, %	20		--
C_4AF, %	9		--

Physical Tests	Results	Retest	ASTM C 618 Spec Limits Type II
Heat of hydration, 7-day, cal/g	74*		70 max
Surface area, m^2/kg (air permeability)	390		280 min
Autoclave expansion, %	0.06		0.80 max
Initial set, min. (Gillmore)	175		60 min
Final set, min. (Gillmore)	265		600 max
Air content, %	9		12 max
Compressive strength, 3-day, MPa (psi)	21.2 (3,080)		10.3 (1,500), 6.9 (1,000[a]) min
Compressive strength, 7-day, MPa (psi)	27.6 (4,000)		17.2 (2,500), 11.7 (1,700[a]) min

REMARKS: [a]Applies only to heat of hydration cement.

* Heat of hydration reported for information only.

Table 3
Fly Ash Chemical and Physical Analyses (Note reference ASTM 1994k)

Company: Monex Resources
Location: Stilesboro, Georgia
Contract No.: ASTM C 618 (ASTM 1994k), Class F
Contract No.:
Project: Roller-Compacted Concrete

Test Report No.: WES -163F-93
Program: Single Sample
CTD No.: 930340
Job No.: ACSAY08001S0001
Date Sampled: 14 Sep 93

10/25/93 Tests complete, material

Chemical Analysis	Results	Retest	ASTM C 618 Spec Limits Class F
SiO_2, %	53.2		--
Al_2O_3, %	25.8		--
Fe_2O_3, %	11.0		--
Sum, %	90.1		70.0 min
CaO, %	--		--
R Factor	--		a
MgO, %	0.9		--
SO_3, %	0.5		5.0, 4.0[a] max
Moisture content, %	0.1		3.0 max
Loss on ignition, %	1.6		6.0, 2.5[a] max
Available alkalies (28-day), %	0.9		1.5 max

Physical Tests	Results	Retest	ASTM C 618 Spec Limits Class F
Fineness (45 μm), % retained	24		34 max
Fineness variation, %	7		5 max
Water requirement, %	96		105 max
Density, Mg/m^3	2.30		--
Density variation	1		5 max
Autoclave expansion, %	-0.03		0.8 max
Pozzolanic activity w/lime, MPa (psi)	6.3 (920)		800 min
Strength activity index w/cement, 7-d, %	72		75[b] min
Strength activity index w/cement, 28-d, %	81		75[b] min

Cement used: Lone Star, Cape Girardeau, MO (158-93)
Lime used: Chemstone

REMARKS: [a]Only applies to Bureau of Reclamation projects.
[b]Note change in testing (ASTM C 618 (ASTM 1994k)).

Table 4
Aggregate Properties (Note reference ASTM 1994a)

Sieve Size	Cumulative Percent Passing			
	Coarse Aggregate		Fine Aggregate	
	Crushed Limestone ASTM C 33 (ASTM 1994a) Size No. 4 (37.5 to 19.00 mm) 930356	Crushed Limestone ASTM C 33 (ASTM 1994a) Size No. 67 (19.0 to 4.75 mm) 940297	Natural Concrete Sand 940236	Limestone Crusher Dust 940304
50 mm	100			
37.5 mm	96			
25.0 mm	49	100		
19.0 mm	17	92		
12.5 mm	3	36		
9.5 mm	1	17	100	
4.75 mm	1	3	100	
2.36 mm		1	75	
1.18 mm			66	
600 μm			59	
300 μm			31	100
150 μm			4	85
75 μm				69
Specific Gravity	2.72	2.74	2.60	2.84
Absorption, %	0.70	0.34	1.32	--

Air-entraining admixtures

Air-entraining admixture (AEA) (940002)

Concrete Mixtures

One nonair-entrained RCC mixture, designated RCCMU-1, and one air-entrained RCC mixture, designated RCCMU-2, were proportioned following the procedures described in EM 1110-2-2006 (HQUSACE 1992b). The mixture proportions for RCCMU-1 and RCCMU-2 are given in Table 5.

Table 5
Roller-Compacted Concrete Mixture Proportions

Material	Nonair-Entrained RCC	Air-Entrained RCC
Portland cement, kg/m^3	115.4	115.4
Fly ash, kg/m^3	56.2	56.2
Natural concrete sand, kg/m^3	753.3	740.7
Coarse aggregate, 37.5-mm NMS, kg/m^3	573.8	581.7
Coarse aggregate, 19.0-mm NMS, kg/m^3	606.9	590.1
Limestone dust, kg/m^3	191.6	188.4
Water, kg/m^3	125.1	108.4
AEA, L/m^3	--	0.39
Water / cement + fly ash ratio	0.73	0.63

Concrete Mixer

The mixer used in this evaluation was a batch-type 1-m^3 (1.308-yd^3) capacity SF 1000 HD Nikko Twin-Shaft Spiral Flow Concrete Mixer. Mixers of this type are commonly known as pugmill mixers. The serial number for the CMD mixer is 7987. This mixer is permanently installed at the CMD laboratory research facility. A plan view of the mixer-paddle configuration is in Figure 1. The mixer is part of an automated batch plant which also includes storage hoppers for the coarse and fine aggregate, silos for cement and fly ash, and scales to determine the mass of each material prior to its introduction into the mixer. Aggregates quantities are determined by mass and transported from the storage hoppers to the mixer on a series of conveyor belts. Cement and fly ash quantities are measured by mass and transported from a hopper to the mixer in an auger. Water is measured by volume and discharged into the mixer from a holding chamber on top of the mixer. AEA is measured by volume in a graduated cylinder inside the batch-plant control room. The AEA is pulled into the graduated cylinder by a slight vacuum and discharged from the cylinder into the mixing water by air pressure. This admixture-dispensing system is the same system commonly found at commercial central-mix concrete plants.

Concrete Production

The batching sequence was the same for all batches of both mixtures. The coarse and fine aggregates were charged into the mixer first with approximately 20 percent of the water. The aggregates and water were mixed approximately 15 sec after which the mixer was stopped. The limestone dust was added manually to the mixer through doors in the side of the mixing

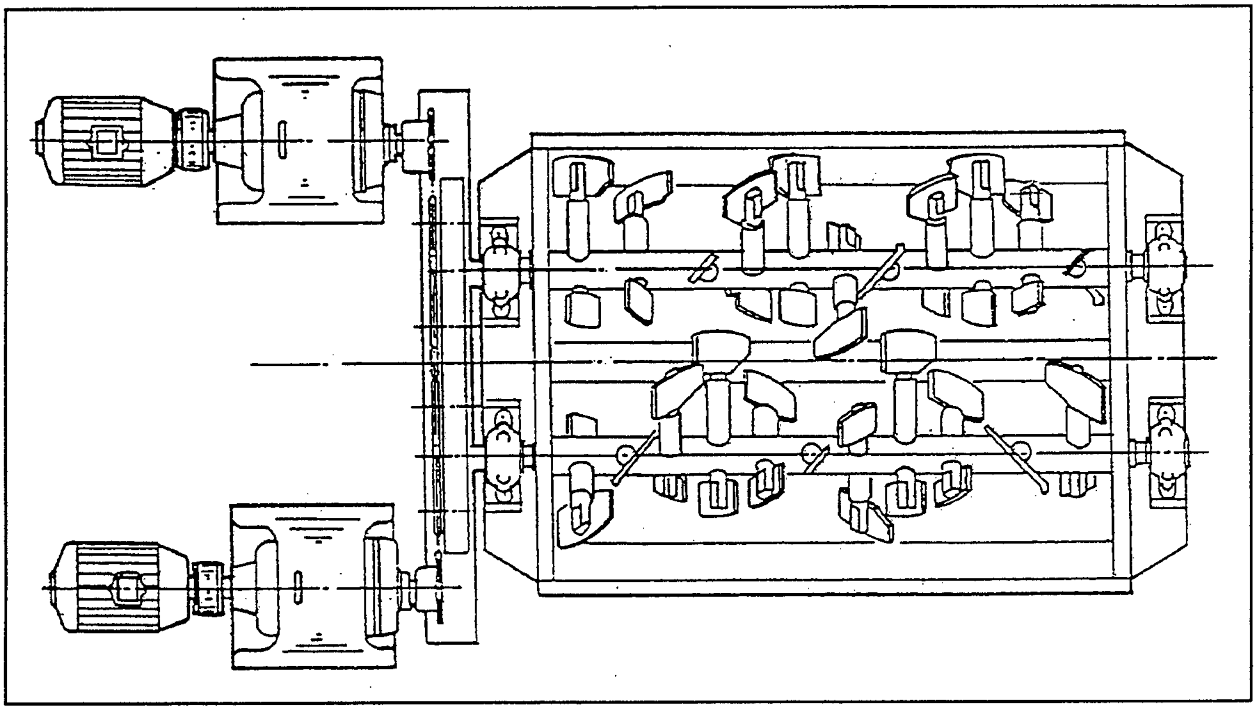

Figure 1. Plan view of mixer-paddle configuration

chamber above the area of the paddles. The mixer was restarted and the cement, fly ash, and remaining water were charged into the mixer. The AEA was added along with the water for those 10 mixtures requiring it. After all materials had been completely charged into the mixer, there was an additional 2 min of mixing. This was believed to be ample mixing time to achieve uniformity. Batch volumes were 0.59 m^3 (20.9 ft^3) for the nonair-entrained concrete and 0.60 m^3 (21.2 ft^3) for the air-entrained concrete. While in actual production it would be uncommon to charge a mixer to only 60 percent of its rated capacity, this is not considered a significant factor in this evaluation. The purpose of this investigation was to evaluate the uniformity of a number of similarly batched mixes under constant conditions; i.e., same materials, same quantities batched, same equipment, same personnel performing tests, etc. Evaluation of the mixer itself was not a criterion.

After mixing was finished, the discharge doors of the mixer were opened and the entire batch of concrete was discharged into a large pan. The batch was then sampled according to ASTM C 172 (ASTM 1994g) from points in each third along the length of the concrete mass that corresponds to the axis of the mixing shafts of the pugmill mixer. Types of tests and numbers of replicates from each sample were as described in CRD-C 55 (USAEWES 1949b). Since this mixer discharges in one operation, the designation "first, middle, and last" does not apply. Instead, the samples were designated, "Left," "Center," and "Right" as sampled from the pan. Given that time could influence some of the results, the sequence in which the samples were taken and evaluated within each batch was randomized using a random number table. Table 6 gives the sequence used.

Table 6
Sampling and Sequence for 10 Batches

Batch	Left one-third	Center one-third	Right one-third
	Strength and Testing Sequence		
1	1	3	2
2	1	3	2
3	2	3	1
4	3	1	2
5	3	2	1
6	2	1	3
7	3	1	2
8	2	3	1
9	2	1	3
10	3	1	2

Tests

After sampling, the test procedures were performed simultaneously by three teams of technicians. The tests were split among the three teams as follows: (a) The first team performed the Vebe consistency tests (CRD-C 53) (USAEWES 1949a), air-content tests (ASTM C 231) (ASTM 1994i), unit-weight of air-free mortar tests (ASTM C 231) (ASTM 1994i) as modified below (following paragraph) and (CRD-C 55) (USAEWES 1949b), and casting of the 152 by 305-mm (6-in.-diam by 12-in.)-high-test cylinders (ASTM C 192) (ASTM 1994h); (b) the second team performed the water-content tests (CRD-C 55) (USAEWES 1949b); and (c) the third team performed the coarse-aggregate washout tests (CRD-C 55) (USAEWES 1949b). This arrangement allowed all test procedures to be completed in a timely manner.

The air-content test procedure, unit-weight of air-free mortar test procedure, and procedure for fabrication of compressive-strength cylinders required modification because of the dry, stiff nature of RCC. The air-content and unit weight of air-free mortar measurements were determined using a Type-B pressure meter. To ensure that the measuring bowl was completely filled, an extension was made to increase the height of the measuring bowl by approximately 150 mm (5.9 in.) during casting of the test sample of RCC. The measuring bowl was filled and consolidation in two equal layers. Consolidation was achieved by attaching the measuring bowl to the Vebe table and vibrating with a 9.07-kg (20-lb) surcharge on top of the RCC. After consolidation, the extension was removed, and the excess RCC leveled with the top of the measuring bowl. The remainder of the test procedure was as described in ASTM C 231 (ASTM 1994i) and CRD-C 55 (USAEWES 1949b). The Vebe vibrating table was also used for molding 152-mm × 305-mm (6-in. × 12-in.) cylindrical specimens for compressive strength determinations. The molds were attached to the table, filled in two equal layers, and consolidated by vibration with a 9.07-kg (20-lb) surcharge on top of the RCC. The specimens were then cured according to ASTM C 192 (ASTM 1994h) in a

moist room meeting the requirements of ASTM C 511 (ASTM 1994j) and broken at 7-days age to determine unconfined compressive strength (ASTM C 39) (ASTM 1994b). Temperature of the freshly mixed RCC was determined according to ASTM C 1064 (ASTM 1994l) All results are given in Appendix A.

3 Analysis and Discussion

Premise

The assumption underlying this analysis is that the concrete in each batch was mixed well enough and long enough to be adequately uniform. If this assumption is true, then the variation among results on the samples taken from the left, center, and right thirds of each batch is a result only of random error due to sampling. The approach to developing uniformity requirements then is to calculate the maximum range of results expected among the three sampling sites, due to these random effects, when concrete is adequately uniform. Then, in an evaluation of a mixing cycle in actual practice, ranges in test results larger than these maxima can be reasonably attributable to lack of uniformity of distribution of the ingredients of concrete within the batch.

Analysis of Data

Prior to estimating these maximum ranges, descriptive statistics were compiled for purposes of comparison of precision among the six test methods used to evaluate mixing uniformity. Data were analyzed in a one-way classification Analysis of Variance (ANOVA) procedure, in which batch number is the single classification variable. Results from each one-third-batch sample were used as replicates for analysis of test-method precision. This analysis assumes that the concrete is homogeneous and, therefore, there are no differences in the concrete represented by the one-third-batch samples. This assumption could not be verified because no subsampling was done. The root mean square error in this analysis represents the standard deviation for each test method, pooled over all 10 batches. These statistics are summarized in Table 7. All calculations were done using Statistical Analysis System (SAS) software.[1]

The purpose of performing the ANOVAs was principally as a tool for estimating test method variability. An auxiliary result was that all six of the ANOVAs showed that there was considerable variation among the 10 batches of concrete. The plan was to make all 10 batches the same way. That there

[1] SAS Institute, Cary, NC.

Table 7
Summary Statistics for Test Data

Test	Mean (over all batches)	Within-Batch Std Deviation	Coefficient of Variation
Nonair-Entrained RCC Mixtures			
Consistency (Vebe)	12.97 sec	1.38 sec	10.62 %
Water content	9.18 %	0.23 %	2.54 %
Coarse aggregate	47.09 %	0.93 %	1.97 %
Compressive strength, MPa	9.4 (1,365 psi)	0.19 (28 psi)	2.07 %
Air-Entrained RCC Mixtures			
Consistency (Vebe)	14.61 sec	1.27 sec	8.71 %
Water content	8.91 %	0.09 %	0.96 %
Coarse aggregate	47.83 %	1.52 %	3.18 %
Compressive strength, MPa	9.41 (1,365 psi)	0.22 (32 psi)	2.32 %
Air content	5.21 %	0.29 %	5.59 %
Unit weight of air-free mortar, kg/m^3	2,305 (143.9 lb/ft^3)	13.94 (0.87 lb/ft^3)	0.60 %
Temperature, °C (°F)	25.6 (78 °F)	0.23 (0.41 °F)	0.52 %

was some deviation from this goal is not particularly important, since within-batch variation is the parameter of interest.

The coefficient of variation (CV) is a useful statistic for comparing variation among the six test methods that give results in different units of measure. CVs for most tests were less than 3 percent. However, the Vebe consistency test (CV = 10.62 percent for nonair-entrained and CV = 8.71 percent for air-entrained) and the air-content test (CV = 5.59 percent) were higher. Consequently, these tests are less sensitive to lack of uniformity in the concrete batch.

The presence or absence of air appeared to affect the precision of two test methods, as measured by the ratio of their variances (F-test). These are the water-content test ($F = 6.53$, $df = 20,20$, $P \le 0.005$) and test for coarse-aggregate fraction ($F = 2.67$, $df = 20,20$, $P \le 0.025$).

Maximum expected ranges in test results for each type of concrete were calculated from ranges in test results among the three determined on each batch. As described above, three samples (left, center, and right) were taken from each batch and tests performed. The range among these three determinations was calculated, then the mean range and the standard deviation in range was calculated over all batches. Upper 95 percent confidence intervals for the range were then calculated for a hypothetical case in which only one batch was sampled and tested (abbreviated testing, para 3.1.3.3. CWGS 03360) (HQUSACE 1994), and for a case in which three batches were sampled and

evaluated (regular testing para 3.1.3.3., CWGS 03360) (HQUSACE 1994). These confidence intervals were calculated as follows:

$$\text{Upper 95 \% CI (n = 1)} = \bar{r} + t_{0.05,\ df} \cdot \left[\frac{s^2}{10} + s^2\right]^{1/2}$$

$$\text{Upper 95 \% CI (n = 3)} = \bar{r} + t_{0.05,\ df} \cdot \left[\frac{s^2}{10} + \frac{s^2}{3}\right]^{1/2}$$

where

$\bar{r}$ = average range

s = standard deviation in range

$t_{.05,\ df}$ = value of Student's t statistic for a 95 percent confidence interval at the number of degrees of freedom (DOF) for the dataset

The DOF were 9 for both nonair-entrained concrete and for air-entrained concrete. Data for 12 batches of nonair-entrained concrete were collected, but data for batches 3 and 7 were discarded because it was believed errors were made in lab procedures. Range statistics are summarized in Table 8.

Table 8
Descriptive Statistics on Range Data

Test	Mean Range among Three Determinations from One Batch	Std Dev in Ranges	Upper 95 % CI (n = 3)	Upper 95 % CI (n = 1)
Nonair-Entrained				
Consistency (Vebe), sec	2.27	1.43	4.40	5.66
Water content, %	0.34	0.33	0.83	1.12
Coarse aggregate, %	1.57	0.96	3.00	3.85
Compressive strength, Mpa (psi)	0.32 (47.0)	0.19 (27.5)	0.61 (87.9) [6.4 %]	0.77 (112) [8.2 %][1]
Air-Entrained				
Consistency (Vebe), sec	2.15	1.25	4.01	5.11
Water content, %	0.14	0.08	0.26	0.33
Coarse aggregate, %	2.61	1.44	4.75	6.02
Compressive strength, MPa (psi)	0.34 (50.0)	0.22 (32.0)	0.67 (97.6) [7.1 %][1]	0.87 (125.8) [9.2 %][1]
Air content, %	0.48	0.30	0.93	1.20
Air-free mortar, kg/m^3 (lb/ft^3)	24.03 (1.50)	10.57 (0.66)	39.72 (2.48)	48.02 (3.06)
Temperature, °C (°F)	0.28 (0.50)	0.29 (0.53)	0.71 (1.29)	0.98 (1.76)

[1]Maximum range expressed as a percentage of mean compressive strength.

These values give the maximum value of range one would expect to see in 97.5 percent of uniformity tests if the concrete were adequately uniform (the other 2.5 percent of tests outside of the 95 percent confidence interval fall below the lower 95 percent limit). Two and one-half percent of tests would exceed this limit even though the concrete was adequately uniform; i.e., there is a 2.5 percent chance of falsely concluding poor mixing when the high values were really due only to effects of random error of sampling and testing.

4 Conclusions

All values support the requirements currently stated in CWGS-03360 (HQUSACE 1994).

The differences in precision of the water content test and the coarse aggregate test apparently caused by the presence of air, previously described, were not large enough to require changing current guidance for those properties.

Since this investigation was designed to evaluate the individual requirements in the mixer uniformity requirements, it is anticipated that these requirements would apply to any type of mixer used to mix RCC. However, it should be pointed out that mixers with less shearing action, such as rotating drum mixers, may not be as effective for mixing RCC. Longer mixing times could be necessary for uniform mixing.

References

American Society for Testing and Materials. (1994). *1994 annual book of ASTM standards.* Philadelphia, PA.

a. Designation C 33-93 "Standard specification for coarse aggregates."

b. Designation C 39-86. "Standard test method for compressive strength of cylindrical concrete specimens."

c. Designation C 127-88. "Standard test method for specific gravity and absorption of coarse aggregate."

d. Designation C 128-88. "Standard test method for specific gravity and absorption of fine aggregate."

e. Designation C 136-84. "Standard method for sieve analysis of fine and coarse aggregate."

f. Designation C 150-92. "Standard specification for portland cement."

g. Designation C 172-90. "Standard practice for sampling freshly mixed concrete."

h. Designation C 192-81. "Standard practice for making and curing concrete test specimens in the laboratory."

i. Designation C 231-89a. "Standard test method for air content of freshly mixed concrete by the pressure method."

j. Designation C 511-85. "Standard specification for moist cabinets, moist rooms, and water storage tanks used in the testing of hydraulic cements and concretes."

k. Designation C 618-92. "Standard specification for coal fly ash and raw or calcined natural pozzolan for use as a mineral admixture in portland cement concrete."

l. Designation C 1064-86. "Standard test method for temperature of freshly mixed concrete."

m. Designation E 380-91. "Standard practice for the use of the international system of units."

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a. Designation CRD-C 53. "Standard test methods for determining consistency and density of roller-compacted concrete using a vibrating table."

b. Designation CRD-C 55. "Test method for within-batch uniformity of freshly mixed concrete."

Appendix A
Test Data

Table A1
Nonair-Entrained Mixtures

Batch	Test		Sample Location Left	Middle	Right	Range
1	Vebe, sec		9.5	9.1	9.0	0.5
	Water content, %	1	8.98	9.22	9.16	
		2	9.04	9.20	9.16	
		AVG	9.01	9.21	9.16	0.2
	Coarse agg., %		49.2	49.6	49.7	0.5
	Compressive strength at 7 days, MPa	1	0.9	1.0	0.9	
		2	1.0	1.0	1.0	
		3	1.1	0.9	1.0	
		AVG	1.0	1.0	1.0	0.0 %

Batch	Test		Sample Location Left	Middle	Right	Range
2	Vebe, sec		20.0	18.7	19.8	1.3
	Water content, %	1	8.28	8.28	8.26	
		2	8.16	8.26	8.36	
		AVG	8.22	8.27	8.31	0.09
	Coarse agg., %		48.5	48.8	48.1	0.7
	Compressive strength at 7 days, MPa	1	2.2	2.5	2.3	
		2	2.2	2.1	2.7	
		3	2.3	2.3	2.5	
		AVG	2.2	2.3	2.5	12.9 %

(Sheet 1 of 6)

Table A1 (Continued)

Batch	Test		Sample Location Left	Middle	Right	Range
3	Vebe, sec		46.6	40.0	35.7	10.9
	Water content, %	1	8.56	8.58	8.86	
		2	8.56	8.42	8.74	
		AVG	8.56	8.50	8.80	0.3
	Coarse agg., %		46.5	46.9	43.9	3.0
	Compressive strength at 7 days, MPa	1	13.8	13.9	13.5	
		2	13.2	13.4	14.0	
		3	13.7	13.6	12.9	
		AVG	13.6	13.6	13.5	0.7 %

Batch	Test		Sample Location Left	Middle	Right	Range
4	Vebe, sec		14.0	9.9	11.5	4.1
	Water content, %	1	9.2	9.22	9.08	
		2	9.2	9.30	9.14	
		AVG	9.2	9.26	9.11	0.15
	Coarse agg., %		44.9	46.3	46.4	1.5
	Compressive strength at 7 days, MPa	1	11.7	11.5	11.8	
		2	11.2	11.6	12.2	
		3	11.4	11.5	11.7	
		AVG	11.4	11.5	11.9	4.3 %

(Sheet 2 of 6)

Table A1 (Continued)

Batch	Test		Sample Location Left	Middle	Right	Range
5	Vebe, sec		10.0	11.0	9.0	2.0
	Water content, %	1	9.24	9.08	9.18	
		2	9.20	9.18	9.18	
		AVG	9.22	9.13	9.18	0.9
	Coarse agg., %		46.3	46.4	46.1	0.3
	Compressive strength at 7 days, MPa	1	9.5	9.5	9.2	
		2	9.7	9.5	9.2	
		3	9.9	9.0	9.6	
		AVG	9.7	9.3	9.3	4.2 %

Batch	Test		Sample Location Left	Middle	Right	Range
6	Vebe, sec		13.3	11.5	15.0	3.5
	Water content, %	1	8.82	8.80	8.88	
		2	8.76	8.74	8.86	
		AVG	8.79	8.77	8.87	0.1
	Coarse agg., %		46.2	45.3	48.2	2.9
	Compressive strength at 7 days, MPa	1	11.6	11.4	10.9	
		2	11.7	11.0	11.4	
		3	11.4	10.9	11.8	
		AVG	11.6	11.1	11.4	4.4 %

(Sheet 3 of 6)

Table A1 (Continued)

Batch	Test		Sample Location Left	Middle	Right	Range
7	Vebe, sec		44.1	37.5	35.9	8.2
	Water content, %	1	9.16	8.86	8.98	
		2	9.20	8.92	8.82	
		AVG	9.18	8.89	8.87	0.31
	Coarse agg., %		44.5	43.8	46.9	3.1
	Compressive strength at 7 days, MPa	1	26.3	29.1	32.8	
		2	27.0	28.8	32.3	
		3	27.5	29.4	30.4	
		AVG	26.9	29.1	31.8	16.7 %

Batch	Test		Sample Location Left	Middle	Right	Range
8	Vebe, sec		7.5	6.5	6.9	1.0
	Water content, %	1	10.46	9.74	10.11	
		2	11.16	9.62	10.02	
		AVG	10.81	9.68	10.07	1.13
	Coarse agg., %		46.9	48.5	49.5	2.6
	Compressive strength at 7 days, MPa	1	9.9	10.1	9.9	
		2	9.7	9.4	10.1	
		3	10.1	9.0	10.2	
		AVG	9.9	9.5	10.1	6.1 %

(Sheet 4 of 6)

Table A1 (Continued)

Batch	Test		Sample Location Left	Middle	Right	Range
	Vebe, sec		10.5	14.8	14.5	4.3
9	Water content, %	1	9.77	9.88	9.29	
		2	9.65	10.00	9.33	
		AVG	9.71	9.94	9.31	0.63
	Coarse agg., %		44.9	47.5	45.8	2.6
	Compressive strength at 7 days, MPa	1	12.5	12.3	12.7	
		2	12.5	12.5	11.9	
		3	12.3	12.9	12.5	
		AVG	12.4	12.6	12.4	1.6 %

Batch	Test		Sample Location Left	Middle	Right	Range
	Vebe, sec		13.2	13.5	12.8	0.7
10	Water content, %	1	9.13	9.43	8.96	
		2	9.25	9.17	9.02	
		AVG	9.19	9.30	8.99	0.31
	Coarse agg., %		47.0	46.1	45.3	1.7
	Compressive strength at 7 days, MPa	1	12.8	11.9	12.3	
		2	12.5	12.0	12.3	
		3	12.6	12.6	12.4	
		AVG	12.6	12.2	12.3	3.2 %

(Sheet 5 of 6)

Table A1 (Concluded)

Batch	Test		Sample Location Left	Middle	Right	Range
11	Vebe, sec		14.8	15.8	12.5	3.3
	Water content, %	1	8.92	9.42	9.14	
		2	9.12	9.20	8.99	
		AVG	9.02	9.31	9.07	0.29
	Coarse agg., %		46.9	47.7	45.6	2.1
	Compressive strength at 7 days, MPa	1	12.7	12.6	12.1	
		2	12.2	12.3	12.2	
		3	12.8	12.4	12.6	
		AVG	12.6	12.4	12.3	2.4 %

Batch	Test		Sample Location Left	Middle	Right	Range
12	Vebe, sec		18.5	19.0	17.0	2.0
	Water content, %	1	9.31	9.33	8.96	
		2	9.24	9.16	8.86	
		AVG	9.28	9.25	8.91	0.37
	Coarse agg., %		47.0	46.6	47.4	0.8
	Compressive strength at 7 days, MPa	1	11.2	11.4	11.4	
		2	11.5	11.0	11.2	
		3	11.4	11.1	11.2	
		AVG	11.4	11.2	11.3	1.8 %

(Sheet 6 of 6)

Table A2
AEA Mixture

Batch	Test		Sample Location: Left	Middle	Right	Range
	Vebe, sec		26.7	29.1	27.1	2.40
1	Water content, %	1	8.60	8.42	8.58	
		2	8.42	8.54	8.56	
		AVG	8.51	8.48	8.57	0.09
	Coarse agg., %		47.3	45.6	50.8	5.2
	Compressive strength at 7 days, MPa	1	11.7	11.7	11.7	
		2	12.2	11.7	11.7	
		3	12.2	11.5	11.0	
		AVG	12.0	11.6	11.6	3.4 %
	Air content, %		4.8	4.8	4.5	0.3
	Air-free mortar, kg/m^3		2,305	2,304	2,341	37
	Temperature, °C		30.6	31.1	30.6	0.5

Batch	Test		Sample Location: Left	Middle	Right	Range
	Vebe, sec		7.0	6.7	6.0	1.0
2	Water content, %	1	8.90	8.96	9.18	
		2	8.88	9.04	9.00	
		AVG	8.89	9.00	9.09	0.2
	Coarse agg., %		48.8	47.6	46.6	2.2
	Compressive strength at 7 days, MPa	1	7.7	7.4	7.7	
		2	7.7	7.8	7.9	
		3	7.8	7.3	7.4	
		AVG	7.7	7.5	7.7	2.6 %
	Air content, %		5.8	5.4	5.2	0.6
	Air-free mortar, kg/m^3		2,312	2,296	2,301	16
	Temperature, °C		28.3	28.3	28.3	0.0

(Sheet 1 of 5)

Table A2 (Continued)

Batch	Test		Sample Location: Left	Middle	Right	Range
3	Vebe, sec		13.7	12.9	14.6	1.7
	Water content, %	1	8.96	9.02	8.97	
		2	9.06	8.92	9.04	
		AVG	9.01	8.97	9.00	0.04
	Coarse agg., %		48.8	47.7	51.3	3.6
	Compressive strength at 7 days, MPa	1	10.2	10.9	10.3	
		2	10.3	10.8	10.3	
		3	10.1	9.9	11.4	
		AVG	10.2	10.5	10.7	4.8 %
	Air content, %		4.1	4.7	4.2	0.6
	Air-free mortar, kg/m^3		2,315	2,341	2,313	28
	Temperature, °C		26.7	26.7	26.7	0.0

Batch	Test		Sample Location: Left	Middle	Right	Range
4	Vebe, sec		14.1	18.9	17.9	4.8
	Water content, %	1	9.18	9.14	9.10	
		2	9.06	9.00	9.12	
		AVG	9.12	9.07	9.11	0.05
	Coarse agg., %		47.1	49.4	49.3	2.3
	Compressive strength at 7 days, MPa	1	9.9	9.7	9.3	
		2	10.3	10.0	10.2	
		3	12.0	10.0	10.3	
		AVG	10.7	9.9	9.9	7.9 %
	Air content, %		4.2	5.0	5.3	1.1
	Air-free mortar, kg/m^3		2,313	2,310	2,336	26
	Temperature, °C		26.1	26.1	26.1	0.0

(Sheet 2 of 5)

Table A2 (Continued)

Batch	Test		Sample Location: Left	Middle	Right	Range
5	Vebe, sec		17.2	15.2	16.1	2.0
	Water content, %	1	8.70	8.82	8.82	
		2	8.88	8.70	8.82	
		AVG	8.79	8.86	8.82	0.06
	Coarse agg., %		47.7	45.9	47.3	1.8
	Compressive strength at 7 days, MPa	1	10.7	10.5	10.5	
		2	9.7	9.7	9.9	
		3	10.3	10.0	10.2	
		AVG	10.2	10.1	10.2	1.0 %
	Air content, %		4.8	4.9	5.2	0.4
	Air-free mortar, kg/m^3		2,315	2,313	2,317	4
	Temperature, °C		28.3	28.3	27.8	0.5

Batch	Test		Sample Location: Left	Middle	Right	Range
6	Vebe, sec		10.8	11.6	12.3	1.5
	Water content, %	1	9.02	9.00	8.66	
		2	8.90	8.82	8.80	
		AVG	8.96	8.91	8.73	0.23
	Coarse agg., %		48.7	46.1	47.8	2.6
	Compressive strength at 7 days, MPa	1	8.5	8.8	9.0	
		2	9.0	9.2	9.2	
		3	9.0	9.0	9.0	
		AVG	8.8	9.0	9.1	3.3 %
	Air content, %		5.3	5.2	5.4	0.2
	Air-free mortar, kg/m^3		2,315	2,291	2,299	24
	Temperature, °C		23.9	24.4	24.4	0.5

(Sheet 3 of 5)

Table A2 (Continued)

Batch	Test		Sample Location Left	Middle	Right	Range
7	Vebe, sec		14.6	14.1	14.0	0.6
	Water content, %	1	8.50	8.68	8.94	
		2	8.72	8.76	8.82	
		AVG	8.61	8.72	8.88	0.27
	Coarse agg., %		50.3	45.9	47.4	4.4
	Compressive strength at 7 days, MPa	1	9.0	8.5	8.5	
		2	9.0	8.7	9.1	
		3	9.1	8.9	9.0	
		AVG	9.0	8.7	8.9	3.4 %
	Air content, %		5.5	5.8	5.8	0.3
	Air-free mortar, kg/m^3		2,293	2,281	2,317	36
	Temperature, °C		23.3	22.8	22.8	0.5

Batch	Test		Sample Location Left	Middle	Right	Range
8	Vebe, sec		15.1	16.9	15.9	1.8
	Water content, %	1	9.10	9.28	9.14	
		2	8.88	9.02	9.12	
		AVG	8.99	9.15	9.13	0.16
	Coarse agg., %		48.1	47.6	47.7	0.5
	Compressive strength at 7 days, MPa	1	8.8	9.3	9.3	
		2	9.5	9.3	9.1	
		3	9.3	9.3	9.4	
		AVG	9.2	9.3	9.3	1.1 %
	Air content, %		5.4	5.0	5.8	0.8
	Air-free mortar, kg/m^3		2,321	2,286	2,296	35
	Temperature, °C		22.8	22.8	22.2	0.6

(Sheet 4 of 5)

Table A2 (Concluded)

Batch	Test		Sample Location: Left	Middle	Right	Range
9	Vebe, sec		10.8	9.6	11.6	2.00
	Water content, %	1	8.88	8.96	8.80	
		2	8.72	9.06	8.78	
		AVG	8.80	9.01	8.79	0.22
	Coarse Agg., %		47.2	46.9	49.3	2.1
	Compressive strength at 7 days, MPa	1	8.5	8.2	9.0	
		2	8.4	8.8	8.5	
		3	8.6	8.9	8.8	
		AVG	8.5	8.6	8.8	3.5 %
	Air content, %		5.8	5.8	5.7	0.1
	Air-free mortar, kg/m^3		2,285	2,280	2,301	21
	Temperature, °C		22.8	22.8	22.8	0.0

Batch	Test		Sample Location: Left	Middle	Right	Range
10	Vebe, sec		12.1	14.8	11.1	3.7
	Water content, %	1	9.24	9.14	9.12	
		2	9.18	9.24	9.12	
		AVG	9.21	9.19	9.12	0.09
	Coarse agg., %		46.2	47.3	47.1	1.1
	Compressive strength at 7 days, MPa	1	8.6	8.3	8.1	
		2	8.3	8.4	8.7	
		3	8.1	7.4	8.3	
		AVG	8.3	8.0	8.4	4.9 %
	Air content, %		5.4	5.8	5.8	0.4
	Air-free mortar, kg/m^3		2,287	2,278	2,294	16
	Temperature, °C		22.2	22.2	22.2	0.0

(Sheet 5 of 5)

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13.ABSTRACT *(Maximum 200 words)*

This report presents the results of a laboratory investigation that was conducted for the purpose of validating mixer-uniformity requirements for roller-compacted concrete. The purpose of the investigation was to verify existing guidance or, if necessary, recommend changes to existing guidance. The investigation included both air-entrained and nonair-entrained concrete.

The results indicate that existing guidance is appropriate for Vebe consistency, water content, coarse aggregate content, compressive strength, and air-content determinations. However, the results indicated that existing guidance could be too restrictive for the unit weight of air-free mortar determinations.

A recommendation was made to consider revising current guidance on the allowable range for unit weight of air-free mortar.

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